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Operations Analysis of Gravity Assisted Rapid Transit

Prepared for

Jet Propulsion Laboratory
California Institute
of Technology

Gibbs & Hill, Inc.

Final Report
October [illegible]
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Gibbs & Hill, Inc.

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October 30, 1981

Mr. Louis Rubenstein
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103

Dear Mr. Rubenstein:

We are pleased to submit our Final Report of our operations analysis of gravity assisted rapid transit systems (GART).

The study has used Gibbs & Hill's computer programs to calculate run times and energy consumption and to prepare realistic signal block designs for both dipped and level guideway configurations. We have used our TRANSPORT network simulation program to perform a detailed analysis of the operations of both systems at a variety of headways and under both normal and abnormal conditions.

Results of our study show that GART significantly reduces energy consumption and can have a somewhat smaller impact on run times. Reducing acceleration rates and the use of coasting also significantly lower the energy consumption of both systems.

In the simulation analysis, the dipped guideway performed as well or better than the level system at headways of two minutes or more. GART systems are best suited to high speed operation. However, the level system has an inherent capacity advantage when it is required to operate at 90 second headways.

We wish to acknowledge the contribution of personnel of the Washington Metropolitan Area Transit Authority who provided us with data describing the type and frequency of abnormal occurrences on the Metro.

Gibbs & Hill would welcome the opportunity to review its study with JPL and to assist in any further steps that would help in further decisions.

We wish to thank you and Mr. Bain Dayman for your generous cooperation on this project.

Very truly yours,

GIBBS & HILL, Inc.

Andrew Bata

Project Manager

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Senior Transportation Engineer

AB/DMW:lg

OPERATIONS ANALYSIS OF GRAVITY ASSISTED RAPID TRANSIT

Prepared for:

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena California 91103

JPL Contract 955934

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FINAL REPORT
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ABSTRACT

This study compares in detail gravity assisted rapid transit (GART) with 6 percent grades before and after each station and conventional systems in terms of energy consumption, run time, line capacity and schedule stability under abnormal circumstances. The study draws on procedures and computer programs that have been applied to engineering designs and studies of actual transit systems.

Parametric analyses of run times and energy consumption include the impact of alternate accelerating and braking levels. The capacity analysis uses a network simulation program to determine the location and severity of all signal delays. Based on results of initial simulations, the block design was revised to eliminate bottlenecks in normal operations. The systems are then compared at headways of 80 to 180 seconds.

One month of incidence reports of a modern operating transit system are reviewed to determine the failures to be simulated. The impact of failures resulting in station delays (30 to 360 seconds), speed limit reduction (20 mph and 30 mph to one or more trains), vehicle performance (75 percent acceleration) are compared at scheduled headway of 90 to 180 seconds.

Results show that GART reduces energy consumption by 8-15 percent and that accelerating and coasting policies can provide similar savings to either system. GART operations perform as well or better than level systems at headways of 120 seconds and more. At 90 second headways the level system performs better due to an inherent advantage at maximum capacity.

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I INTRODUCTION

The Jet Propulsion Laboratory has been investigating methods for reducing capital and operating costs of rapid transit systems. In their study "Alternative Concepts for Underground Rapid Transit Systems" for the U.S. Department of Transportation (DOT-TST-77-31, March, 1977) JPL concludes that new approaches in design and construction, including the use of gravity assisted rapid transit (GART), can significantly reduce both capital and operating costs for new mass transit systems. Building the mined tunnels required for underground GART guideways has recently been made more economical through the use of tunnel boring machines (TBM). In GART systems, guideways have grades before and after each station to reduce energy requirements in the braking and accelerating modes.

The JPL study finds the higher construction cost of providing the dips in the guideways is offset by the elimination of some vent shafts and smaller station environmental systems. This as well as operating savings result from the reduced energy consumption. Some savings in vehicle costs might also be possible.

The purpose of the present study is to determine the impact of the dipped guideways on energy, run times and schedule operations using Gibbs & Hill's TRANSPORT network simulation computer program. Detailed analyses of the run time, energy consumption, line capacity and the ability to maintain service under disruptive conditions for both level and dipped guideways are made. The purpose of these analyses is to provide a reasonable basis for comparison of the two systems, not to optimize either.

The present study is divided in three parts.

1. The first consists of the establishment of the study parameters including the development of data bases.

2. The second part consists of the analysis of run times and energy consumption for alternate guideway configurations and train performance characteristics. This includes an examination of alternate locations for crossovers in the dipped scheme. These analyses are performed using Gibbs & Hill's train performance computer program, TRAPER.

3. In the third part of the study, Gibbs & Hill's network simulation program, TRANSPORT, is used to analyze operations under normal and abnormal conditions at a variety of headways. TRANSPORT is able to analyze bottlenecks and to determine the impact of various delays on operations. Although theoretically GART possesses advantages in both accelerating and braking modes, questions arose about performance under peak conditions when delays are likely to

occur. Were these delays to result in trains braking on downgrades and accelerating on upgrades, the advantages would instead become liabilities.

TRANSPORT, which contains detailed models of the network, signal system and train performance, is able to quantify differences between the level and dipped systems in the areas of system capacity, run time and the ability to withstand and recover from various failure conditions. The simulation is able to do this precisely and on a global scale by modelling in detail the interaction between trains including the incidence of all restrictive speed commands. The failure conditions studied were chosen after a review of actual transit operating statistics.

A prerequisite to the simulation study is the development of signal systems for both the dipped and level guideways. Gibbs & Hill has drawn on its experience in the design of high capacity systems to develop signal block layouts capable of maximizing capacity. A family of computer programs conceived for this purpose and which has been used in the design of a number of transit systems was applied in this study.

II SUMMARY AND CONCLUSIONS

In this section the principal results and conclusions of the analyses discussed in Sections IV, V, VI and VII, and dealing with run time and energy consumption, crossover location, line capacity and failure impact, respectively, are covered. The results are based on comparison of two hypothetical guideway configurations, each similar in plan to the proposed Southern California Rapid Transit District system. However, the study is parametric in nature to preserve generality. Results are obtained for interstation distances ranging from 2600 feet to 13000 feet, for headways between 80 and 180 seconds, and for delay conditions of varying severity. Figures III-1 and III-2 show the guideway profiles.

a. Run Time and Energy Consumption

This analysis has been conducted using Gibbs & Hill's TRAPER single train performance calculator (TPC) computer program. The program has been widely used to perform similar computations for a number of operating rapid transit systems.

Comparisons between the dipped and level systems cover the effects of: interstation distance, acceleration and braking rate. The braking rate variation provides some indirect measure of the benefit of coasting since a lower braking rate causes trains to end acceleration and begin the station stop farther upstream. A more precise estimate of these benefits requires the explicit modeling of coasting policies. Results also cover criteria for the civil design of vertical curves. This is because the common design allowance of 100 feet of vertical curve for each one percent of grade change precludes the use of 6 percent grade in the shortest interstation distance, 2600 feet. A 6 percent grade is used for all the longer interstation distances.

Taking the last item first, two alternate vertical curve standards are considered: 60 feet and 80 feet of vertical curve for each one percent grade change. These criteria reduce the length of the vertical curve and permit the grades to be located closer to the stations. This has a small effect on run times.

The main effect of the baseline criterion is that it restricts the grades to 3 percent when stations are only 2600 feet apart. A 6 percent grade using the 100 foot criterion would need 600 foot vertical curves. Four vertical curves, each 600 feet long, separation of at least one train length between each, plus a 300 foot station add to 3600 feet. The 80 foot criterion enables a grade of 3.75 percent and the 60 foot criterion enables a grade of 5.0 percent.

The impact of the various vertical curve standards is greatest at the 2600 foot interstation pairs. The 80 foot criterion reduces run time by 0.4 percent and energy consumption by 1.4 percent compared with the 100 foot criterion. The 60 foot criterion would reduce run time by 1.1 percent and energy consumption by 5.5 percent. At the 5200 foot interstation distances the benefit is much less. The 60 foot criterion would reduce run time by 0.4 percent and energy consumption by 1.6 percent. The benefit diminishes at greater interstation distances since the proportion of energy expended maintaining speed increases. In view of the small incremental benefit in this study and the uncertain stature of these alternate criteria, the 100 foot vertical curve criterion was retained for the dipped guideway scheme.

The analysis shows that dipped guideways can significantly reduce energy consumption. Running time is also improved, but to a lesser extent. Table II-1 summarizes the results presented in Tables IV-3 and IV-6. It shows the range of percent increase or decrease that can be achieved by dipped or level guideways, at full or half acceleration, using full or 75 percent braking rate. The range is taken over the four different interstation distances tested for each case. As shown, all three measures reduce energy consumption but only the dipped guideways cut run time.

These results tend to confirm the energy savings reported in the JPL Study (op.cit.). The JPL study used 10 percent grades and different vehicle performance characteristics than are used in this study. Consequently, the total energy consumption on both dipped and level guideways in the JPL study is considerably higher than in this study. However, the percentage savings of the dip, at full acceleration and full braking, is about 15 percent in each study for the interstation distances of 5200 feet and more where the maximum dip is realized. At the shortest interstation distance a saving of about 8 percent is forecast in each study.

b. Crossover Location

Two locations for crossovers on the dipped system are considered. One is near the station before the dip begins. The other is in the middle of the dip. Operating requirements, such as the need to make smooth, programmed station stops even when the crossover signal is red or to turn back before descending the dip, preclude crossovers at the two shortest interstation distances studied, 2600 and 5200 feet. If crossovers are needed there, then a level guideway might be used.

TABLE II-1

Summary of Run Time and Energy Consumption Changes

Scheme	Acceleration & Braking	Run Time Changes	Energy Consumption Changes
Level	Full	----------------Baseline----------------	
Dipped	Accel, Brake	- 1.6% to - 3.6%	- 7.0% to -16.5%
Level	Half Accel,	+ 8.1% to +17.5%	-10.8% to -29.9%
Dipped	Full Brake	+ 3.5% to +12.8%	-26.4% to -36.9%
Level	Full Accel,	+ 3.4% to + 8.6%	- 1.2% to -5.1%
Dipped	3/4 Brake	+ 1.2% to + 5.7%	-12.1% to -19.3%
Level	Half Accel,	+11.6% to +23.9%	-12.2% to -34.4%
Dipped	3/4 Brake	+ 7.2% to +19.5%	-28.8% to -42.0%

Notes: Range is over four interstation distances

Car characteristics given in Appendix are those of the Washington Metro car. Maximum depth of dips is 60 feet.

If the crossover is located near the station, the beginning of the dip is farther from the station to avoid locating the crossover on a vertical curve and to allow space between the crossover and the dip for trains to reverse direction. (See Figure V-1a.) This displacement of the dip slightly reduces its benefits for normal operations. Locating the crossover between the dips, as shown in Figure V-1b, does not affect normal operations but is disadvantageous when rerouting is required. Trains must decelerate for the crossover and then accelerate again. The crossover speed limit in each case is 22 mph.

The alternate crossover locations are compared under two operating scenarios: when operations are normal and the crossover is not used and when the crossover is needed to switch tracks. In the first case, putting the crossover near the station saves both energy (6.8 percent to 8.7 percent) and run time (1.8 percent to 2.7 percent).

However, when the crossover is needed for switching, locating the crossover in the dip, between the grades, saves energy (41.7 percent to 48.1 percent) and run time (6.3 percent to 7.2 percent) depending on interstation distance. The reason for the larger differences in energy and run time is that trains must accelerate twice--once leaving the station and again when clearing the crossover. The run time advantage of putting the crossover near the station also results in improved headways because of the opposing moves involved.

c. Line Capacity

The capacity analysis is based on the use of Gibbs & Hill's TRANSPORT network simulation computer program. Other Gibbs & Hill programs were used to design the signalling systems for the dipped and level guideways.[1] All of these programs have been used in the past to perform similar tasks for operating rapid transit systems.

Several results stem from this part of the study.

1. The dipped system operates most efficiently at a moderately high speed, 55 mph or more. This is because trains accelerate to 55 mph at the bottom of the dip and are at this same speed on their stopping profile at the bottom of the upgrade leading to the next station. If the speed is lowered to increase capacity then trains will power up the lower portion of the upgrade.

[1] For a description of these programs and techniques, see D.M. Weiss and D.R. Fialkoff, "Analytical Approach To Railway Signal Block Design," ASCE Transportation Engineering Journal, February 1974.

2. If designed to operate only at top speed, the dipped system would have a lower minimum headway than the level system. Although each system operates well at two-minute headways at top speed, neither does well at 90-second headways.

3. To operate 90-second headways, it is necessary to reduce speeds in the station approaches. At these reduced speeds, the level system has an inherently greater capacity.

4. The final signal block designs, revised after analysis with TRANSPORT, permit minimum headways of 87-seconds on the dipped system and 81-seconds on the level system. This makes operation at 90 second headways more stable on the level system than on the dipped system. These values of minimum headway are near the theoretical limits, although further revision of the block designs might permit a small reduction.

The minimum headway is the lowest headway at which trains traveling at given speeds can operate if always separated by at least safe braking distance. This usually occurs when one train is leaving a station and the following train is approaching the station. At top speeds the critical point on the dipped system occurs when the following train is at the bottom of the upgrade. In this case the safe braking distance on the dipped system is less than that of the level system because of the influence of the grade on braking.

However, as speed is reduced to lower the minimum headway, the safe braking distance on both the dipped and level systems decreases and the critical point moves closer to the station entrance. At the station entrance however the safe braking distance for the dipped system is greater than that of the level system because of the influence of the downgrade leaving the station.

To transmit a given speed command in a block, a length of track equal to the safe braking distance must be clear downstream. A 40 mph command in the block preceding the station requires a clear track for 1240 feet on the level system. Since this length includes track downstream of the station, the downgrade on the dipped system raises the safe braking distance to 1970 feet.

Note that the safe braking distances are required by the signal system even where a train is scheduled to stop in a station. This is because station stopping is not enforced by the signal system. The assumptions for safe braking distance are more conservative than those of the nominal station stopping brake rate. See Section III.c.

d. Failure Impact

An analysis of the incident reports and summary operating statistics for the Washington Metro was used to identify typical failures and to determine the range of durations of each. Since the purpose of this analysis is to distinguish the impact of failures on the dipped and level system, major failures that result in system paralysis or call for the intervention of a dispatcher were not studied.

Four types of failures are simulated: minor station delays (30 and 60 seconds), major station delays (180 and 360 seconds), acceleration limit for one train (75 percent), acceleration limit for all trains (three stations and systemwide, 50 percent) and top speed limit for all trains (one station, 20 mph and 30 mph). All failures are simulated on both the dipped and level guideways at each of three operating headways: 90 seconds, 120 seconds and 180 seconds. A total of 54 experiments are performed.

In each experiment, a fleet of trains at each headway is dispatched at one terminal, the failure occurs and the run time of each train in the fleet is measured to each station. These times are compared to a control run time in which no failure occurred. The difference in run time for each train in the fleet is tabulated to determine the impact of the failure. The results of the failure experiments are discussed in detail in Section VII.

In general, the dipped system performs as well or better than the level system at headways of 120 seconds or more. At 90 second headways the level system is usually superior due to its inherent capacity advantage.

Station Delays

In these experiments one train is held at the fourth station for between 30 and 360 additional seconds extra. The results are that when delays are major (180 seconds or 360 seconds) or when headways are at their peak (90 seconds) the impact of the failure is more severe on the dipped system. This is because the minimum headway of the level system is less than that of the dipped system (81 seconds versus 87 seconds).

The impact on the level system is greater in the minor delays. The reason for this turnabout is that when the system is less saturated and trains run at top speed the dipped system has more capacity. This is because at higher speeds the safe braking distance is greater and causes the critical headway point to occur farther from the station. On the dipped system it occurs at the bottom of the dip instead of the entrance to the station

as at minimum headway. At the bottom of the dip, the safe braking distance is less than that of the level system.

Acceleration Limits

In general, acceleration failures cause smaller delays on the dipped system because motive power provides only a portion of the total power. This is shown in the following table.

Failure	Run Time Increase (seconds)	
	Dipped System	Level System
Half Acceleration, 3 Stations	26	34
Half Acceleration, Systemwide	145	203
75% Acceleration, One Train	50	69

The minimum headway acceleration failures increase the time for trains to clear away from stations. When this occurs on the dipped system, the minimum headway becomes greater than the 90 second operating headway. Thus although delays are less than the level system at 180 and 120 seconds, the dipped system cannot operate at 90 second headways while the level can.

Top Speed Limits

The top speed limit is imposed between the first and second stations. The 20 mph limit adds 60 seconds of run time to the dipped system and 64 seconds to the level system. The 30 mph limit increases run times 31 and 32 seconds respectively. The 30 mph limit does not create any additonal delays for either system at any headway. The 20 mph limit permits scheduled headways of 180 or 120 seconds but both systems break down during 90 second operations.

III STUDY PARAMETERS

The parameters developed for this study fall in the following categories:

- Guideway Characteristics - Plan, Profile, Design Criteria
- Train Performance - Acceleration, Braking, Top Speed
- Signal System Capability - Headways, Run times
- Schedules
- Failure Conditions

A requirement of the study is that the consultant use data on file or that is readily available to facilitate timely completion. Accordingly a number of the parameters used in the study are those of the Washington D.C. Metro. These parameters are typical of modern high-performance rapid transit systems.

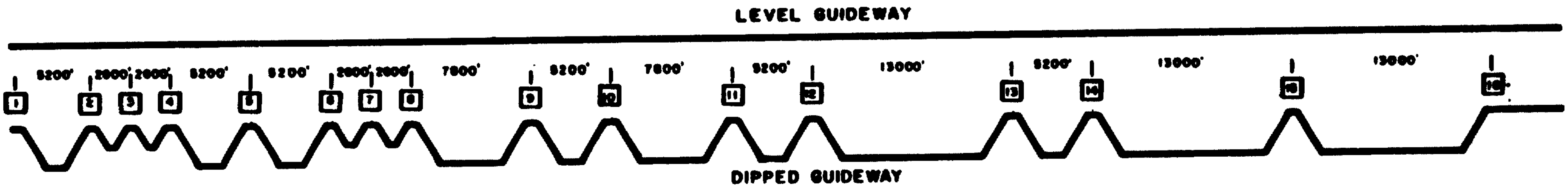
a. Guideway Characteristics

The system contains 16 stations over its 18.2 mile length, and is loosely configured along the lines of the proposed Southern California Rapid Transit System. See Figures III-1 and III-2. To facilitate the analysis, a modular network is developed. Four station pairs are 2600 feet apart, six 5200 feet apart, two 7800 feet apart, and three are 13000 feet apart.

Two track profiles are established. One track is level throughout. The other track has stations in the identical position but with a maximum grade of 6 percent for 1000 feet approaching and leaving each station. The 6 percent grade was selected as being the steepest grade which would have a high probability of working if the concept was valid. The study therefore avoids the objective of trying to optimize the value of the dip grade.

In laying out the guideway, a vertical curve criterion of 100 feet of curve for each one percent of grade change was initially selected. This is the minimum standard selected for the Washington D.C. Metro. Such a criterion however limits the grades between the closest station pairs (2600 feet) to 3 percent. The length of the vertical curve also has an impact on run time and energy consumption.

Figure III-1 Guideway Schemes



KEY

[1] - STATION (300' LONG)

DIPPED GUIDEWAY DESIGN CRITERIA

VERTICAL CURVES: 100' FOR EACH 1% CHANGED

DIPS: 3% 700' LONG ON 2600' STATIONS (21')

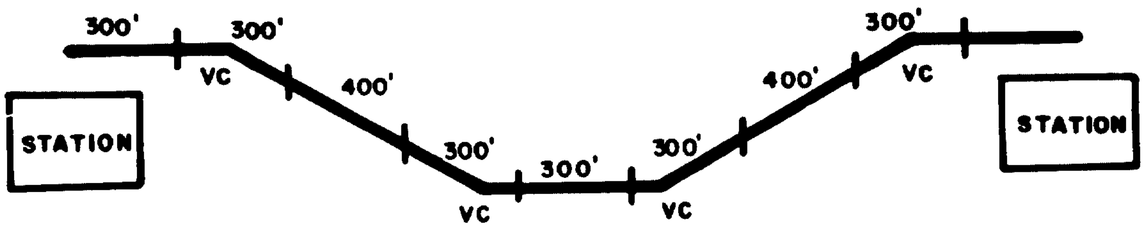
6% 1000' " " OTHER " (60')

MINIMUM DISTANCE BETWEEN VERTICAL CURVES:

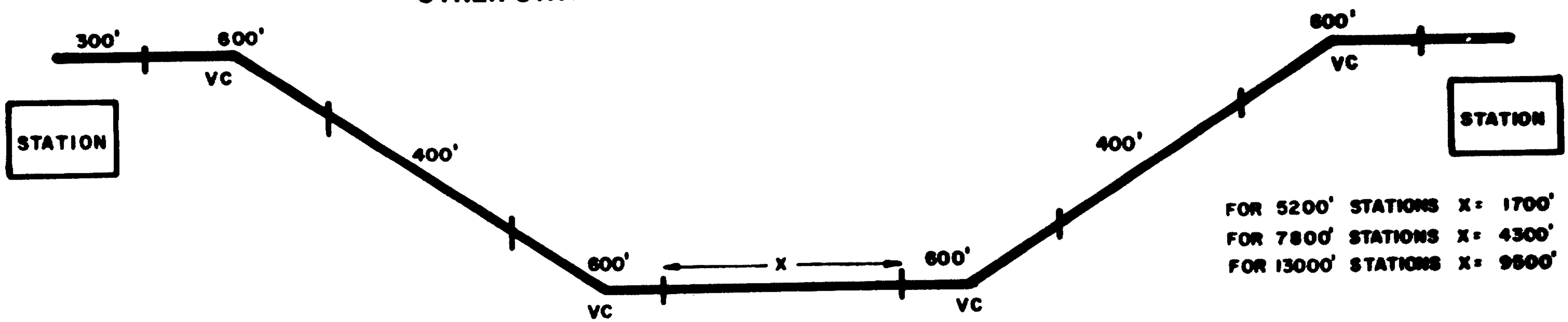
ONE TRAIN LENGTH (300')

Figure III – 2 Guideway Profiles

2600' STATION SPACING (700' LONG DIP, 3% GRADE, 21' DEPTH)



OTHER STATION SPACINGS (1000' LONG DIP, 6% GRADE, 60' DEPTH)



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In the belief that this criterion could be relaxed, JPL requested a greater analysis of vertical curve criteria. It was found that the criteria established for the Washington and Miami Metros are the same: 100 feet of vertical curve for each 1 percent grade change (minimum) and 200 feet preferred. MARTA and BART have somewhat more complex criteria which depend on speed and whether the vertical curve is at a sag or crest. Analyses of run time and energy consumption were conducted for three criteria, 60 feet, 80 feet and 100 feet of vertical curve per percent grade change. The results, presented in the following section, showed that the minor advantage of using either of the two less conservative criteria is not sufficient to neutralize the controversy it might provoke. Accordingly, the 100 foot standard was retained for the balance of the study.

The length of the vertical curve connecting grade changes of 3 percent (in the 2600 foot stations) is 300 feet. The other vertical curves which connect 6 percent grade changes are 600 feet. In all cases a track section of at least one train length (300 feet maximum - four 75-foot cars) separates the vertical curves. Stations are 300 feet long. The relatively short train lengths reflect the JPL conclusion that savings in construction costs outweigh higher crew costs.

b. Train Performance

The nominal train performance characteristics are based on the vehicle performance of the Washington car. The initial values for acceleration and braking of this car are 3.0 mphps and 2.2 mphps respectively. The car performance characteristics are similar to those of the other modern transit cars used in this country. Specific data is contained in the Appendix.

c. Signal System

The modeling of a high-capacity transit system, with headways of two minutes or less, necessitates the representation of the signal system. The signal system is the primary medium by which delays to one train are transmitted to following trains. A central control system can mitigate these effects to some degree. However, none was established for the proposed operation.

The design criterion for each of the signal systems was the operation of 90 second headways at the highest possible speeds. Initially, blocks were laid out to theoretically permit 85-second headways. During the simulation phase bottlenecks were uncovered. As a result, signal block lengths were reduced in critical areas to permit shorter headways at somewhat lower speeds. Gibbs & Hill employed the same methods and criteria in the layout of the signal systems for both the dipped and level schemes as were used in its design for the Washington Metro and

other systems. Safe braking distance calculations for the signal system are based on a 25% derating of the nominal brake rate, a six-second reaction time including an allowance of two seconds of full acceleration.

d. Schedules

Schedules were developed for the simulation studies for headways between 80 and 180 seconds. All experiments were simulated on both the level and dipped systems. In the capacity analysis, headways are 80, 90, 120, 140, and 180 seconds. Headways of 90, 120 and 180 seconds were simulated in the failure analysis. Station dwell times are 25 seconds, line speed is 75 mph. All trains stop at all stations.

Turnaround at terminals is excluded from the analysis. Trains are put in service at one end of the line and removed at the other end.

e. Failure Conditions

A review of operating incident reports of the Washington Metro formed the basis for the failures analyzed in the study. These failures consisting of excess dwell in stations, top speed limitations and acceleration reductions, are discussed in detail in the section on Analysis of Failure Impacts.

IV ANALYSIS OF RUN TIME AND ENERGY CONSUMPTION

The advantages of the dipped guideway, reported in the JPL study, cited above, stem from potential reductions in run time and energy consumption. These benefits affect operating costs directly and could also reduce capital costs for vehicles and environmental control systems.

To quantify these advantages for the proposed system, Gibbs & Hill made a number of train performance computer (TPC) runs using its TRAPER program. We have used this program before on studies of run time and energy consumption for a number of transit systems including the New York City Transit Authority (NYCTA), Massachusetts Bay Transit Authority (MBTA), Bay Area Rapid Transit District (BARTD) and the Port Authority Trans-Hudson (PATH) as well as a number of commuter railroads.

The analyses enable comparisons to be made between the level and dipped systems for nominal vehicle performance (baseline), for half acceleration, and using 75% of the nominal braking rate. The half acceleration run serves the dual purpose of providing a sensitivity measure should a car less powerful than the WMATA car be used and of providing an estimate of the potential impact of derating car performance as an operating policy. The reduced braking rate causes trains to initiate their station stop farther from the station and thus indirectly measures the effect of coasting in the station approach.

TPC runs for each set of train performance characteristics were made for each of the four interstation distances selected. All three vertical curve standards were studied for the shortest distance. In this case the tighter the standard, the lower the possible grade on the dip. A 5% grade can be obtained if only 60 feet of vertical curve are required for each one percent of grade change. A 3.75% grade is possible if 80 feet of vertical curve are required per percent but only 3% grade can be incorporated with the 100 foot per percent grade standard. A 6% grade is used for all interstation distance of 5200, 7800 and 13000 feet.

Tables IV-1 and IV-2 contain the energy and run time for trains running at full and half acceleration levels, respectively, for a variety of interstation guideway configurations. The run time is insensitive to the vertical curve standard even for the 2,600 foot interstation distance, in which the tighter vertical curve criteria permits steeper grades to be used on the dip. In these cases the vertical curves are all 300 feet long, but the grades vary. The propulsion energy consumption is slightly more sensitive than run time especially for the 2,600 foot distance where the steeper grades reduce energy requirements.

TABLE IV-1

ENERGY AND RUN TIME COMPARISONS - FULL ACCELERATION

Interstation Distance (Feet)	Guideway, Vertical Curve	Run Time (Seconds)	Propulsion Energy (kWhr)
2,600	60' (5% grade)	52.9	13.8
	80' (3.75% grade)	53.3	14.4
	100' (3% grade)	53.5	14.6
	Level Track	54.4	15.7
5,200	60' (6% grade)	77.6	18.3
	100' (6% grade)	77.9	18.6
	Level Track	79.2	21.3
7,800	100' (6% grade)	100.9	20.8
	Level Track	104.7	24.9
13,000	100' (6% grade)	147.0	24.7
	Level Track	150.8	28.8

Note: Dipped guideway has a 6% grade at all distances except 2,600 feet where the grade depends on the vertical curve criterion, 60', 80' or 100' of length per 1% grade change.

Car characteristics given in Appendix are those of the Washington Metro car. Maximum depth of dips is 60 feet.

TABLE IV-2

ENERGY AND RUN TIME COMPARISONS - HALF ACCELERATION

Interstation Distance (Feet)	Guideway, Vertical Curve	Run Time (Seconds)	Propulsion Energy (kWhr)
2,600	60' (5% grade)	60.1	9.2
	80' (3.75% grade)	60.8	9.6
	100' (3% grade)	61.3	9.9
	Level Track	63.9	11.0
5,200	60' (6% grade)	85.8	13.9
	100' (6% grade)	86.7	14.2
	Level Track	92.7	17.0
7,800	100' (6% grade)	110.0	17.4
	Level Track	116.9	21.8
13,000	100' (6% grade)	156.1	21.2
	Level Track	163.0	25.7

Note: Dipped guideway has a 6% grade at all distances except 2,600 feet where the grade depends on the vertical curve criterion, 60', 80', or 100' of length per 1% grade change.

Car characteristics given in Appendix are those of the Washington Metro car. Maximum depth of dips is 60 feet.

TABLE IV-3

COMPARISON OF RUN TIME, ENERGY CONSUMED DIPPED VS LEVEL GUIDEWAY USING FULL BRAKING RATE

Interstation Distance (Feet)	Configuration	Percent Change	
		Run Time (%)	Propulsion Energy (%)
2,600	Level, full acc.	----Baseline------	
	Dipped, full acc.	-1.7	-7.0
	Level, half acc.	17.5	-29.9
	Dipped, half acc.	12.8	-36.9
5,200	Level, full acc.	----Baseline------	
	Dipped, full acc.	-1.6	-12.7
	Level, half acc.	17.1	-20.1
	Dipped, half acc.	9.5	-33.3
7,800	Level, full acc.	----Baseline------	
	Dipped, full acc.	-3.6	-16.5
	Level, half acc.	11.7	-12.4
	Dipped, half acc.	5.1	-30.1
13,000	Level, full acc.	----Baseline------	
	Dipped, full acc.	-2.5	-14.2
	Level, half acc.	8.1	-10.8
	Dipped, half acc.	3.5	-26.4

Note: Dipped guideway has a 6% grade at all distances except 2,600 feet where the dip is at 3%. All vertical curves based on 100' of length per 1% grade change.

Car characteristics given in Appendix are those of the Washington Metro car. Maximum depth of dips is 60 feet.

We conclude that there is some benefit to further investigation of vertical curve criteria, especially for short interstation distances. However, for the simulation phase of the project, the common professional design standard of 100 feet of vertical curve (minimum) per percent grade change is used. The primary measurement in the simulation run time differentials is entirely insensitive to these criteria.

Table IV-3 is the main result of this section. It compares the run time and energy consumption of the dipped (using the 100 foot vertical curve standard) and level systems. The level guideway with full acceleration is the baseline for each interstation distance. Percentage changes in run time and energy consumption for the dipped guideway at full and half acceleration and the level guideway at half acceleration are shown. As shown, the dipped guideway can substantially reduce energy consumption. At full acceleration propulsion energy consumption of the dipped guideway is from 7.0% to 16.5% less than the level guideway, depending on interstation distance, with run times lowered two to four percent. Reducing the acceleration level of the cars from full to half also offers a major energy saving for both systems . The penalty in run time is less for GART, however, because the dip itself contributes a significant fraction of the total acceleration. (A 6% dip is equivalent to 1.2 mphps of acceleration.)

At half acceleration, the propulsion energy savings of the dipped system range from 26.4 percent to 36.9 percent. The run time penalties range from 3.5 percent to 12.8 percent. The relative advantage of the dip, which in our design has a fixed size, diminishes with interstation distance because trains reach and maintain the speed limit, during which there is neither a penalty nor savings associated with the dipped system or a reduced acceleration level.

We also simulate the effect of a reduced braking rate on energy and run time calculations. The lower braking rate, 75 percent of normal , causes trains to decelerate for stations at a greater distance from stations. In some cases, trains can't reach top speed before having to brake for a station. The effect on propulsion energy consumption is the same as if the train were coasting in the station approach.

Tables IV-4 and IV-5 are parallel to Tables IV-1 and IV-2 but represent the reduced braking level. The percentage propulsion energy savings, as shown, are greatest for the 2600' interstation distance where a train doesn't reach the top speed. In this case, the lower braking rate means trains brake earlier and from a lower speed. Table IV-6 presents the percentage changes in run time and energy consumption of trains on the level or dipped guideway at full or half acceleration level with the 75 percent

braking rate compared to the baseline of the level guideway at full acceleration. This is a further demonstration that the reduced braking rate or other coasting policy combined with the half acceleration and the dipped guideway can have a significant impact on energy consumption: dipped system energy savings range from 28.8 percent to 42.0 percent with run times increasing from 7.2 percent to 19.5 percent. The reduced braking rate also cuts energy consumption on the level system, although at a somewhat greater increase in run time.

TABLE IV-4

ENERGY AND RUN TIME COMPARISONS FOR 75% BRAKING RATE - FULL ACCELERATION

Interstation Distance (Feet)	Guideway, Vertical Curve	Run Time (Seconds)	Propulsion Energy (kWhr)
2,600	60' (5% grade)	57.0	13.0
	80' (3.75% grade)	57.3	13.4
	100' (3% grade)	57.5	13.8
	Level Track	58.3	14.9
5,200	60' (6% grade)	82.7	17.2
	100' (6% grade)	83.0	17.6
	Level Track	86.0	20.4
7,800	100' (6% grade)	106.2	20.1
	Level Track	109.9	24.6
13,000	100' (6% grade)	152.6	24.0
	Level Track	156.0	28.4

Note: Dipped guideway has a 6% grade at all distances except 2,600 feet where the grade depends on the vertical curve criterion, 60', 80' or 100' of length per 1% grade change.

Car characteristics given in Appendix are those of the Washington Metro car. Maximum depth of dips is 60 feet.

TABLE IV-5

ENERGY AND RUN TIME COMPARISONS FOR 75% BRAKING RATE - HALF ACCELERATION

Interstation Distance (Feet)	Guideway Vertical Curve	Run Time (Seconds)	Propulsion Energy (kWhr)
2,600	60' (5% grade)	63.8	8.4
	80' (3.75% grade)	64.5	8.8
	100' (3% grade)	65.0	9.1
	Level Track	67.4	10.3
5,200	60' (6% grade)	90.6	12.9
	100' (3% grade	91.6	13.2
	Level Track	97.2	16.3
7,800	100' (6% grade)	115.3	16.9
	Level Track	122.1	20.8
13,000	100' (6% grade)	161.7	20.5
	Level Track	168.2	25.3

Note: Dipped guideway has a 6% grade at all distances except 2,600 feet where the grade depends on the vertical curve criterion, 60', 80' or 100' of length per 1% grade change.

Car characteristics given in Appendix are those of the Washington Metro car. Maximum depth of dips is 60 feet.

TABLE IV-6

COMPARISON OF RUN TIME, ENERGY CONSUMPTION OF DIPPED AND LEVEL GUIDEWAYS AT 75% BRAKING RATE WITH FULL BRAKING RATE

Interstation Distance (Feet)	Configuration	Percent Change (Level, Full Accel Full Brake is baseline. See Table IV-1 for values). Run Time	Propulsion Energy
2,600	Level, full acc. 75% brake	7.1%	- 5.1%
	Dipped, full acc. 75% brake	5.7	-12.1
	Level, half acc. 75% brake	23.9	-34.4
	Dipped, half acc. 75% brake	19.5	-42.0
5,200	Level, full acc. 75% brake	8.6	- 4.2
	Dipped, full acc. 75% brake	4.7	-17.4
	Level, half acc. 75% brake	22.8	-23.5
	Dipped, half acc. 75% brake	15.7	-38.0
7,800	Level, full acc. 75% brake	5.0	- 1.2
	Dipped, full acc. 75% brake	1.5	-19.3
	Level, half acc. 75% brake	16.6	-16.5
	Dipped, half acc. 75% brake	10.1	-32.1
13,000	Level, full acc. 75% brake	3.4	- 1.2
	Dipped, full acc. 75% brake	1.2	-16.7
	Level, half acc. 75% brake	11.6	-12.2
	Dipped, half acc. 75% brake	7.2	-28.8

Note: Dipped guideway has a 6% grade at all distances except 2,600 feet where the dip is at 3%. All vertical curves based on 100' of length per 1% grade change.

Car characteristics given in Appendix are those of the Washington Metro car. Maximum depth of dips is 60 feet.

V ANALYSIS OF CROSSOVER LOCATION

An analysis was performed to determine the best location for crossovers on the dipped guideway. Two placements were tested. One location is near the station, before the dip and the other is down in the middle of the dipped section. The analysis covers only the two longer interstation distances, 7800 feet and 13,000 feet. The assumed guideway design criteria do not permit crossovers in dipped guideway configurations with less than 5600 feet between stations. An under-and-over crossover design used to connect tracks when pl-ced one above the other would require an even greater distance between stations than the side-by-side scheme considered.

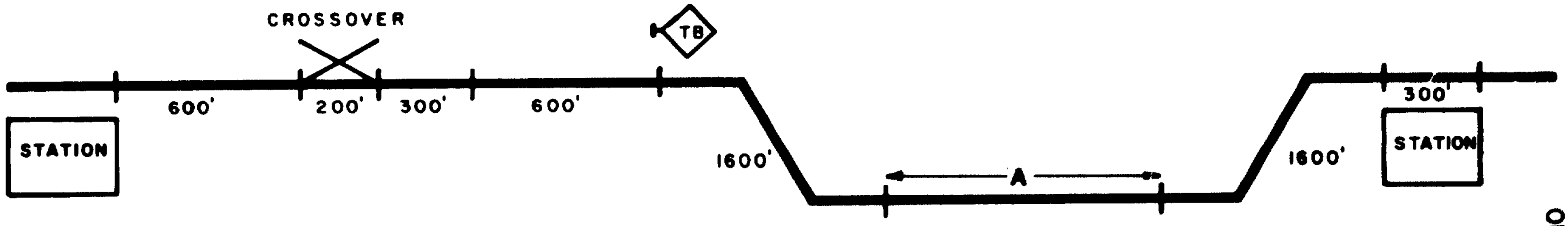
a. Design Criteria

A number 8 crossover, about 200 feet long, with a speed limit of 22 mph is used. In the first case (Figure V-1a), the crossover is located before the dip, 600 feet from the station. This separation enables a train to make a normal stop in the station if the signal at the crossover is displaying a stop command. Six hundred feet is the safe braking distance for 22 mph. Following the crossover, one train length (300 feet) plus the braking distance (600 feet) is on level track before the dip begins. A turnback is located at the end of the 600 foot block to enable trains to reverse direction. The vertical curve for the dip therefore begins 1700 feet from the station.

In the second case, the crossover is in the dip, with turnbacks located 900 feet from either end, as in Figure V-1b. If the crossover is closer than 1100 feet to the base of the dip, trains would brake on the dip to hold speed to safely traverse the crossover when it is in the reverse position, or to stop if there is a stop signal at the crossover.

Some of the parameters of the dipped guideway could be changed to permit crossovers to be located in the more closely spaced stations. If the grade were only 3 percent, the total length of track allocated for the four vertical curves per station pair would drop from 2400 feet to 1200 feet. In addition, since trains can more easily stop and accelerate on this grade, the turnback might be located on the dip or on the vertical curve. This would permit crossovers to be located within the configuration of the 5200 foot interstation distance.

Figure V-1A Crossover Near Station

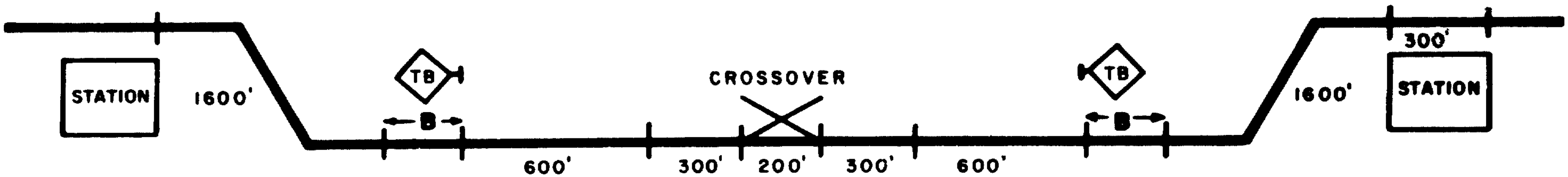


For 7800' Interstation Distance A: 2600'

For 13000' Interstation Distance A: 7800'

TB =Turnback Point

Figure V-1B Crossover Amidst Dip



For 7800' Interstation Distance B: 1150'

For 13000' Interstation Distance B: 3750'

b. <u>Results</u>

Six sets of TPC runs were made. In all cases, trains start at one station and proceed to the next without stopping. In the straight moves, they bypass the crossover and stay on the same track. In the reverse moves, trains switch tracks at the crossover. Half-acceleration runs were made for each straight move, primarily as a sensitivity test. Each set consists of a run for the 7800 foot and the 13000 foot interstation distance. The results are shown in Table V-1.

As the table shows, the run time and energy consumption for the straight (normal) moves are slightly lower when the crossover is in the dip. The run time is lower because the location of the dip is nearer to the station and permits trains to clear away from the station faster. The energy consumed is less because the high performance cars modeled do not reach the speed limit before completely descending the dip. When the crossover is above the dip, trains reach the speed limit before the bottom of the dip. The full energy saving benefits of the dip are thus not obtained. The half acceleration test was made to determine the sensitivity of this result. Even at half acceleration trains reach line speed before descending the dip if the dip begins 1700 feet from the station. They do so closer to the bottom, however, so the difference in energy consumed is considerably narrower.

It, therefore, seems likely that regardless of the eventual vehicle capability there will be a benefit to locating the crossover in the dip whenever operations are normal. However, on those less frequent occasions when it would be necessary to use the crossover, a significant penalty would be paid in run times, energy consumption and operating efficiency.

Locating the crossover near the station saves about three seconds and two kilowatt hours in normal operation (regardless of the interstation distance) but costs about ten seconds and nine to twelve kwhr per train during rerouting. The large energy differential occurs because trains accelerate twice if the crossover is in the dip: once leaving the station and again leaving the crossover. The greater run time results from time spent braking and accelerating at the crossover. In practice the run time differential would be even greater because the signal system would ensure that trains with a minimum braking capability are down to the crossover speed before entering. Trains with the nominal braking rate would achieve this speed well upstream.

There are operational advantages as well for locating the crossover nearer the station. Short-turning is easier since trains don't have to go so far past the station. Headways could also be lower both for following and opposing moves, due to the lower run time.

TABLE V-1
CROSSOVER ANALYSIS
ENERGY, RUN TIME COMPARISONS

Crossover Location/Move	Run Time (seconds)	Energy Consumption (kWhr)
7800' Stations		
Above Dip/Straight	103.7	23.0
In Dip/Straight	100.9	20.8
Above Dip/Reverse	123.6	20.4
In Dip/Reverse	132.5	28.9
Above Dip/Straight/Half Acc	114.6	18.4
In Dip/Straight/Half Acc	110.0	17.4
13000' Stations		
Above Dip/Straight	149.7	26.5
In Dip/Straight	147.0	24.7
Above Dip/Reverse	169.7	24.3
In Dip/Reverse	180.5	36.0
Above Dip/Straight/Half Acc	160.7	22.2
In Dip/Straight/Half Acc	156.1	21.2

NOTE: Crossover position "Above Dip" is shown in Figure V-1A.
Crossover position "In Dip" is shown in Figure V-1B.

VI ANALYSIS OF LINE CAPACITY

Section IV deals with energy and run time advantages of the dipped guideway. The analysis is based on the use of a TPC, which models one train at a time. The network or systemwide implications are covered in the simulation phase of the project, addressed in this and the following section.

There are two systems which control transit operations: the signal system and the central control or dispatching system. The signal system is inherently local. The speed trasmitted to a train depends only on its location and that of the downstream train. Such factors as time-of-day and whether this or other trains are on schedule are ignored. This is the province of the central controller who can act in response to the global situation.

Modelling the central control system is outside the scope of this study. We have however postulated that a basic goal of the dispatcher of a dipped guideway would be to prevent or minimize signal delays in station approaches which would cause trains to power up the hill. The results of an attempt to implement this strategy using the signal system are discussed.

a. Development of Signal System

Block designs for both the dipped and level systems were initially developed with design objectives permitting 90-second headways at speeds of 55 mph. This is a high speed for such short headways, but is chosen for the following reasons:

1. Trains on the dipped system reach a speed of 35 mph at the bottom of the dip if no power is applied. In the usual case, when full power is used, trains reach 55 mph. The speed command sent to trains leaving a station should enable trains to traverse the dip at maximum performance.

2. Trains reach the beginning of the upgrade to the next station at 55 mph on their stopping profile. If a lower speed were used, trains would have to power up a portion of the upgrade.

The dipped system, therefore, is most energy efficient at a moderately operating high speed. If the speed is lowered to increase capacity, then energy efficiency is reduced. The level system has no such dependence on high speed. A block design for a level system could be prepared which would permit even shorter headways although at lower speeds and consequently longer run times. For the sake of comparisons, however, the design criteria for both systems were the same. The block designs that resulted have the same number of blocks and the same number of speed

commands in each block. The cost of the signaling systems should therefore be the same.

The block designs that were prepared were tested with TRANSPORT at a variety of headways between 180 and 80 seconds. Neither block design would enable trains to operate for any length of time at headways of 90 seconds or less, due to insufficient slack headway. The block designs were, therefore, refined to eliminate the bottlenecks to shorter headways. The resulting designs were again tested with TRANSPORT.

The modified block designs again have the same number of blocks as each other and the same number of speed commands in each block. The costs of each system are thus similar and would be slightly higher than the initial system due to the somewhat greater number of blocks. The modified block designs permit considerably shorter headways. The minimum headway for the level system has been reduced from 94 seconds to 81 seconds and for the dipped system from 94 seconds to 87 seconds.

The lower minimum headway for the level system stems from an inherent capacity advantage of this type of system (discussed below) and from the particular design parameters chosen for this study. The primary design factors are the high-performance car (the acceleration curve is the same as that of the Washington Metro car) and the steep grades of 6 percent. In combination, they result in a car speed of 55 mph at the base of the downgrade. In the stations that are one mile apart, a train would reach the bottom of the downgrade while the preceding train is in the next station if eighty second headways are scheduled. This results in a stop command being issued which in turn results in an unstable operation. This stop command, which would be issued when dispatching headways are well below 90 seconds, might be avoided by adopting one or more of the following:

- Reduce the acceleration level of the train when such headways are encountered;
- Issue lower speed limits on the downgrade;
- Reduce the size of the grade.

The second measure would require trains to use brakes on the downgrade. The third measure would affect all trains regardless of headway. The first measure can be achieved in the design of the control system. For example, the control system for the Washington Metro can modify the acceleration level of cars as a function of the current lateness of trains, or in response to power system failures.

b. Simulation Experiments

TRANSPORT has been used to test the capacity of all the block designs developed for the dipped and level systems. To do this, five fleets of trains, each with a different internal headway, were dispatched from stations D01 at the south end of the dipped line and L01 at the south end of the level line. The headways between trains in fleets were: 180 seconds, 140 seconds, 120 seconds, 90 seconds, 80 seconds. TRANSPORT calculated run times for all trains in each fleet and produced details regarding all signal delays encountered. The run times to stations D08 in the middle of the dipped line and to D16 at the end and to stations L08 and L16 in the same positions on the level line, presented in Table VI-1 for selected trains, are measures of system performance. The results are based on the initial block design.

As Table VI-1 shows, trains on both the dipped and the level systems travel substantially at top speed, with a minimum of signal delays at headways of two minutes (120 seconds) and more. When trains are dispatched at 90-second headways, signal delays are frequent and trains travel generally at 55 mph instead of 75 mph. The fact that a stable run time profile is not reached even after the twelfth train in the 90-second fleet, shows that the 90-second headway operation is marginal for both the dipped and level systems with these block designs. This was further borne out when an attempt was made to operate at 80-second headways. Run times for both systems increased and trains were often stopped in station approaches due to signal delays.

The same experiments were repeated with the revised block design. The results, shown in Table VI-2, are generally similar for Fleets 1, 2, and 3. However, in Fleet 4, the run times stabilize in each case and at values less than those in Table VI-1. Note that at 90-second headways, the run time difference between dipped and level trains at the 12th train is less than that at the first train when trains are running at top speed. This shows the higher capacity of the level system.

The results of the simulation for Fleet 5 are presented in Table VI-2. They were omitted from Table VI-1 because trains were not able to operate at even the 90-second headway schedule. Table VI-2 shows that the level trains can operate at these headway levels while the dipped trains cannot. Run times for the dipped trains are nearly as great as those of the level system. The stabilization of runtimes at 80 second headways on the level system shows that the minimum headway is in the neighborhood of 80 seconds, actually 81 seconds. The 87 second minimum headway on the dipped system is reflected in Table VI-2 by the marginal stabilization of run time at 90 second headways and its absence 80 second headways.

TABLE VI-1

RUN TIMES TO THE MIDDLE (8TH) AND LAST (16TH) STATION.
INITIAL BLOCK DESIGN.

Fleet/ Train	Dipped System		Level System	
	D08 (Min-Sec)	D16 (Min-Sec)	L08 (Min-Sec)	L16 (Min-Sec)
Fleet 1 H = 180				
Train 1	9-46	27-39	10-06	28-42
2	9-46	27-39	10-06	28-42
3	9-46	27-39	10-06	28-42
Fleet 2 H = 140				
Train 1	9-46	27-39	10-06	28-42
2	9-52	27-50	10-06	28-46
11	9-52	27-50	10-06	28-46
Fleet 3 H = 120				
Train 1	9-46	27-39	10-06	28-42
2	9-55	27-51	10-15	28-54
3	9-57	27-57	10-15	29-01
11	9-57	27-57	10-15	29-04
Fleet 4 H = 90				
Train 1	9-46	27-39	10-06	28-42
2	10-03	28-06	10-26	29-18
3	10-07	28-23	10-32	29-40
8	10-23	29-12	10-57	30-19
9	10-25	29-18	11-02	30-24
10	10-29	29-23	11-06	30-28
11	10-31	29-26	11-11	30-33
12	10-35	29-30	11-15	30-37

TABLE VI-2

RUN TIMES TO THE MIDDLE (8TH) AND LAST (16TH) STATION.
FINAL BLOCK DESIGN.

Fleet/ Train	Dipped System		Level System	
	D08 (Min-Sec)	D16 (Min-Sec)	L08 (Min-Sec)	L16 (Min-Sec)
Fleet 1 H = 180				
Train 1	9-46	27-42	10-06	28-42
2	9-46	27-42	10-06	28-42
3	9-46	27-42	10-06	28-42
Fleet 2 H = 140				
Train 1	9-46	27-42	10-06	28-42
2	9-52	27-48	10-06	28-42
11	9-52	27-48	10-06	28-42
Fleet 3 H = 120				
Train 1	9-46	27-42	10-06	28-42
2	9-58	27-54	10-06	28-46
3	10-01	28-05	10-06	28-45
11	10-01	28-06	10-06	28-45
Fleet 4 H = 90				
Train 1	9-46	27-42	10-06	28-42
2	10-07	28-12	10-18	29-10
3	10-12	28-27	10-23	29-33
8	10-18	29-11	10-23	29-46
9	10-15	29-09	10-23	29-46
10	10-16	29-06	10-23	29-46
11	10-16	29-06	10-23	29-46
12	10-18	29-08	10-23	29-46
Fleet 5* H = 80				
Train 1	10-25	29-20	10-30	29-54
2	10-34	29-27	10-35	30-03
3	10-41	29-35	10-41	30-10
9	11-25	30-28	11-02	30-49
10	11-32	30-36	11-06	30-55
11	11-38	30-42	11-02	30-58
12	11-46	30-49	11-00	31-01
13	11-53	30-57	11-02	31-03

* Trains in Fleet 5 follow Fleet 4 to speed convergence to the steady state. Thus, the higher run time for Train 1.

c. Line Capacity Differences

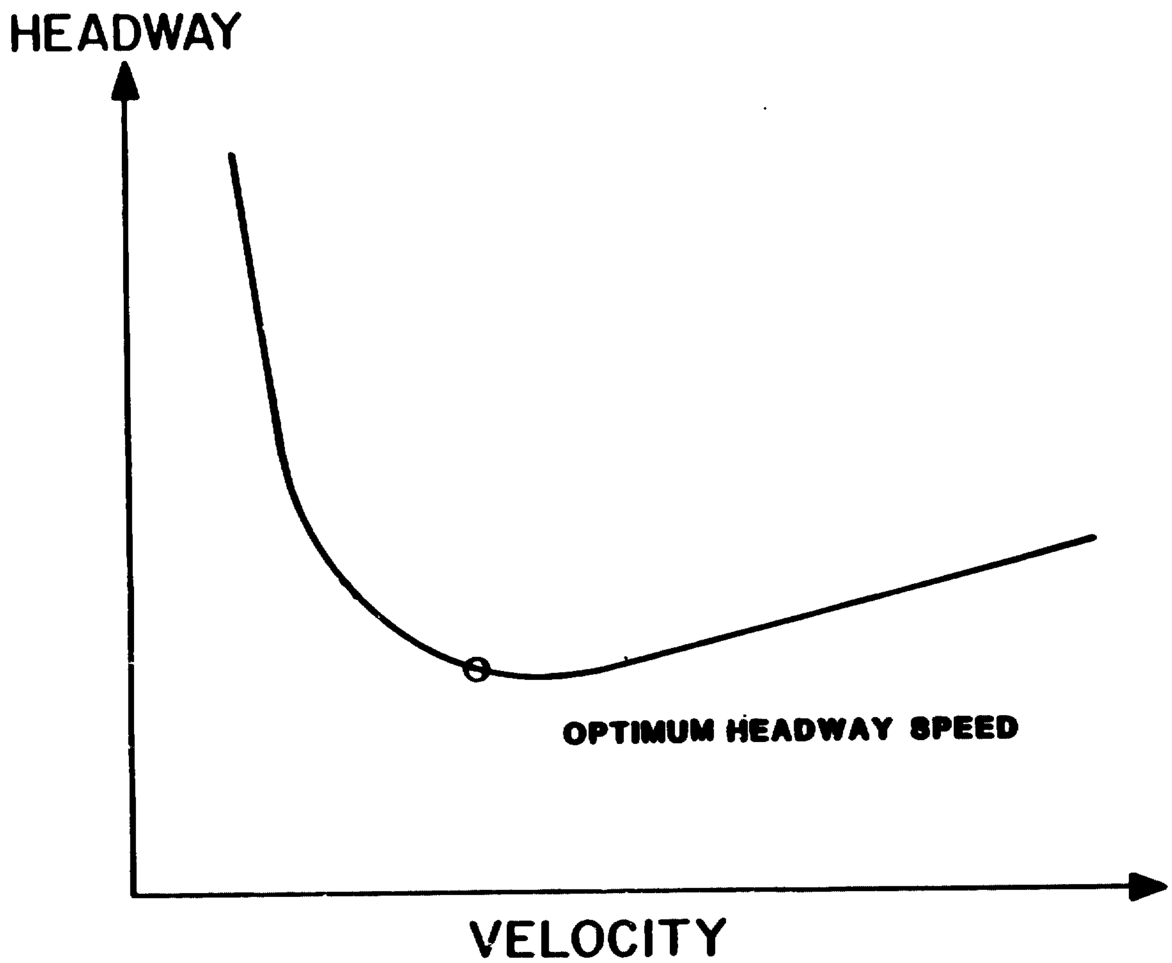
In any system, when two trains, at a given speed, follow each other, they must be separated by their safe braking distance. If the speed and grade vary, so will the SBD. The minimum headway is the smallest interval at which such trains can be dispatched and always be safely separated. The critical point at which they are exactly SBD apart usually occurs when one train is approaching a station and the leading train has completed its dwell and just cleared the station area. The minimum headway is the time to travel from the follower's to the leader's position. The calculation of SBD is based on the following train maintaining the signalled speed. However the schedule requires the train to slow down and dwell in the station and then accelerate.

If a curve of minimum headway vs. operating speed were drawn, it would have the form of Figure VI-1. The reason for the optimum point is that trains are separated by SBD plus one train length. At low speeds the time to travel one train length is great. At high speeds the time to travel the braking distance, which is proportional to the square of the speed, is great. In between lies the optimal value, typically around 35 or 40 mph. A full discussion of this is given in the book Urban Rail Transit by Lang and Soberman (MIT Press).

The minimum headway of the dipped and level systems is initially determined for two trains running at maximum speeds. In this case the minimum headway for the dipped system is actually lower than that of the level system, but not low enough to permit 90 second headways. The dipped system has a lower minimum headway because the critical point occurs when the following train is at the bottom of the dip. The SBD on the dipped system (2690 feet) is lower than the level system (3440 feet) at 75 mph because of the influence of the upgrade.

As the design speed for peak headways is reduced to enable the 90 second headway operation, the safe braking distances are reduced and the critical point moves closer to the station. That is, the critical point moves from the bottom to the top of the grade on the dipped system. At the top of the grade the SBD on the dipped system (1970 feet) exceeds that of the level system (1240 feet) at 40 mph, because of the influence of the downgrade following the station. This is the reason for the ultimate capacity advantage of the level system.

The dipped system then could have a greater capacity than the level system at maximum speeds, but has a lower capacity at the speeds required for 90 second headway operation.



Headway vs. Speed

Figure VI-1

In general, the dipped system is more suited to high speed operation because of the high speed reached at the end of the downgrade leaving stations. This speed should be maintained until trains reach the bottom of the next upgrade, where they coast and brake to a stop. Operating at less than 55 mph reduces the energy savings of the dipped system because trains would motor up the lower part of the upgrade. Should delay conditions cause trains on the dipped system to brake on downgrades or motor on the upgrades, the energy consumption could actually exceed that of the level system. Such delays do not effect the energy consumption of the level system.

It should be mentioned that there are very few rail transit systems or routes which operate at headways shorter than two minutes. Most heavy rail systems have adequate passenger carrying ability at this headway. Thus the capacity advantage of the level system drops as design headways rise above 90 seconds.

d. Analysis of Extended Control Lines

We postulated that one potential problem with dipped systems is that if not properly controlled, trains will receive signal delays in the areas approaching stations. These restrictive signals which would cause trains to slow down or stop on the upgrade would negate energy savings and cause operational problems. To mitigate this problem, we developed an alternate set of control lines wherein a train leaving a station would not receive the top speed command unless the next station was clear even though it would be safe to transmit this command with much less distance between trains. The effect of this should be to transfer the delay from the station approach to the beginning of the level section. In this area the trains would be held there to 55 mph until the next station is clear.

The analysis of the simulation runs, however, showed that this particular implementation was ineffective. The lengthened control lines created delays where none would have occurred. Run times suffered without any benefit to capacity. Nonetheless the control system that would be required for a dipped guideway system should have as one objective the elimination of restrictive signals on the upgrades and downgrades of the system to maximize run time and energy consumption benefits. However, a more flexible approach than this simple one, hard-wired into a signal system, would be required.

VII ANALYSIS OF FAILURE IMPACTS

In addition to the capacity analysis already performed, which resulted in the refinement of the signal system and verified the minimum headway that can be scheduled, a set of operating contingencies have been developed to test the relative performance of the dipped and level systems. These contingencies are based on typical operating problems and occur for various durations and headways.

To perform this analysis we have reviewed one week of incident reports and one month of summary statistics of the Washington Metro. Reportable incidents randomly occurred in from 2 percent to 6 percent of the trips. About 80 percent of the reported incidents involved no delay. Less than 0.5 percent involved a delay of 10 minutes or more (one of the 250 trains on a line each day). Failure impact, including possible rerouting, depends on headway, time of day, and other factors.

Motor overloads, doors, brakes, and automatic train control (ATC) problems were the principal causes of incidents. These often were due to stuck brakes or doors, lost indications or displays, blown fuses and loose plugs. The large ridership on the Metro also creates a demand for cars which occasionally exceeds the supply, resulting in the cancellation of some trains.

In addition to reportable incidents, trains may be delayed by unreportable causes. An example is held doors in a station. Trains also are delayed because the train ahead is slow. It is not always possible to pinpoint the cause of lateness. The Metro considers three minutes late to be excessive. About 95 percent of the trains are on time.

a. <u>Types of Failures</u>

We distinguish four classes of failure.

Station Delays-Major	This includes failures of a train at stations. Examples are: a door malfunction, stuck brakes, inadvertent application of emergency brakes and consequent waiting time to recharge. Such delays can last from three to twelve minutes. Stuck handbrakes and the inability to key up are problems that occur at terminals. These can last for five to twenty minutes, but the delay to passengers is less if a train can be brought in on the other track. Thus terminal delay to passengers are usually less than one headway.

Station Delays-Minor	This category includes excess dwell times and temporary failures. Duration of these is from a few seconds to one minute.
Delays En Route -	Reduced Acceleration. Acceleration of a train may be reduced by defective or cutout equipment, or by a power outage affecting all or part of the line.
Delays En Route -	Reduced Top Speed. The top speed of trains is reduced when proceeding through a work area, or running through a station. Failures which result in a truck being cut out (hence partial acceleration as well as partial braking) could also cause a lowered top speed. Car failures which result in the cutout of the signal system might cause a lower top speed. If a train is given a manual block and instructed to move to a given yard or terminal, the central supervisor might want the train to move as fast as possible. If such a manual block is not made a lower speed could be set.

b. <u>Failures Simulated</u>

Part of the usual simulation of a failure is the action of the central supervisor. He may take a variety of actions to mitigate the problem. The scope of our analysis, however, does not include central control. We do not determine whether any rerouting would be performed or whether trains would be held in stations.

In the simulations a failure occurs, trains are delayed, the system restores itself (if possible) and normal operation resumes. The significant measurement is the differential impact of the failure and the speed of restoration on the level versus the dipped system. Accordingly severe failures which would in practice be deflected with a compensating strategy are not included in our analysis. The maximum failure duration is six minutes. All failures are simulated at three headways: 90, 120 and 180 seconds on both the level and dipped systems.

Station Delays

At the fourth station on each system a train is held at the station for 30 and 60 seconds to simulate minor failures and three and six minutes to simulate more severe failures. Failures significantly greater than six minutes often result in operator intervention to mitigate the problem or result in a major

degradation of system performance that would halt operation on both the level and dipped systems.

Acceleration Limit

Three runs simulate different failures which cause acceleration reductions. The acceleration of one train is limited to 75 percent of its nominal value to represent a propulsion failure on the train. The acceleration of all trains is limited to 50 percent of nominal value for the first three stations and for the entire line to simulate failures to one substation or a systemwide power reduction, respectively.

Top Speed Limit

The top speed of trains between the first and second station is limited to 20 mph to simulate operation through a work area, and to 30 mph to simulate an additional limit and to provide a sensitivity measurement.

c. Design of Experiments

Each failure is simulated on each system (level and dipped) and at each scheduled headway (90, 120 and 180 seconds). There are nine failures:

1-4) 30, 60, 180 and 360 second station delays to one train
5-6) 20 and 30 mph top speed limits, one station, all trains
7) 75% acceleration limit to one train, entire run
8) 50% acceleration, all trains, first three stations
9) 50% acceleration, all trains, entire run

The experimental design is factorial because each failure is simulated with all combinations of the other two variables (system and headway). There are thus a total of 54 separate experiments in the failure analysis. In each experiment, a fleet of trains is dispatched for 30 minutes. The fleet comprises 11, 16, and 21 trains when scheduled headways are 180, 120 and 90 seconds, respectively. Longer fleets at shorter headways are modelled because the extent of the failure is more pervasive. Where the failure directly impacts one train, the first in the fleet is failed.

The impact of the failure is measured by comparing the run times of the trains in the fleet to the run times for the corresponding fleet, absent the failure, as presented in Table VI-2, above. The difference in run times, with and without the failure, for example, to the fifth train in a fleet of trains at 90 second headways on the level system, is tabulated as the delay. The results of the capacity analysis thus serve as the experimental control for the contingency analysis.

d. <u>Results</u>

In the following sections, the results of each simulation experiment are discussed. Generally the failures are divided as transient delays which impact one train directly, such as the station delays, and permanent delays which affect all trains, such as the systemwide acceleration failure or the top speed limit. As is shown, the number of trains affected by transient delays depends on the system and headway. Except in the case of the six-minute station dwell failures, the delays are eventually dissipated.

The permanent delays affect the system capacity or minimum headway. In this case, if the minimum achievable headway is increased above the scheduled headway, delays build up continuously. If the scheduled headway is greater than the minimum headway, the main effect usually is that all trains have their run time increased by the value of the delay.

Station Delays - Minor

The 30-second station delay does not cause any delay to following trains at 180-second headways. The delay is entirely absorbed by the system slack. At 120-second headways, there are slight delays on both the dipped and level systems, but those on the level system are greater. This is because at 120 second headways trains run at top speeds where the dipped system is more effective, as described in Section VI.c.

Figure VII-1 contains the graphs of delay vs. the numerical position of a train within its fleet for the Station Delays - Minor (30 seconds). Train 1 is the first train in the fleet, train 2, the second, etc. The delay tabulated is the difference in run times for trains in this fleet, and the corresponding control fleet on the same system, at the same headway, run in the capacity analysis.

At 90 second headways, the delays in the level system are considerably less extensive: only three trains are delayed more than ten seconds, including the train with the initial failure. Seven trains on the dipped system are delayed ten or more seconds.

This pattern, wherein delays at longer headways are less severe on the dipped system but more severe at shorter headways, repeats for 60-second station delays. The results are presented in Figure VII-2. There are no delays at three-minute headways: the slack headway (the difference between operating headway and the minimum headway) is considerably greater than the magnitude of the delay. Although some signal delays developed upstream of the failure, which occurred at the fourth station, none went as far

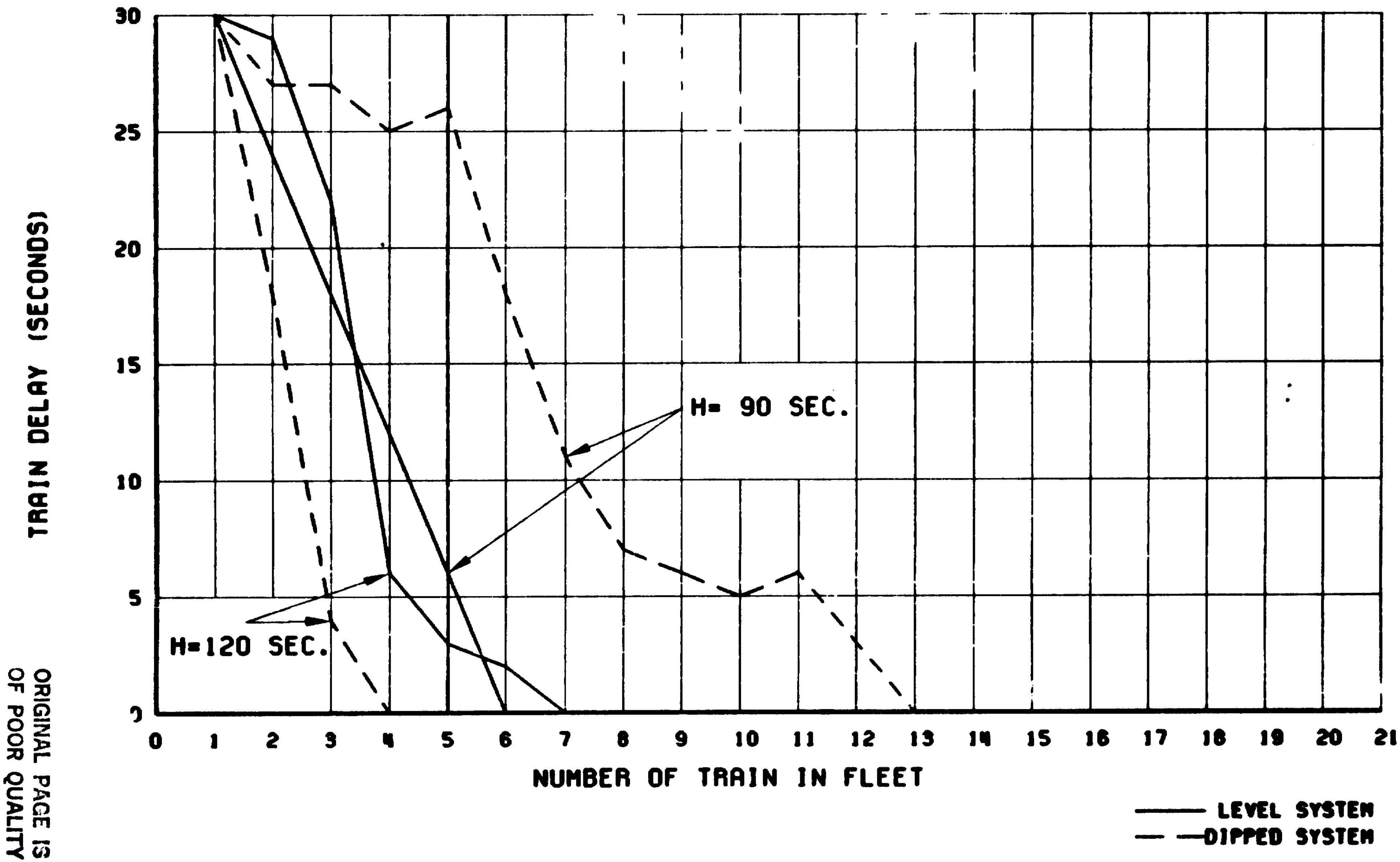


FIGURE NUMBER VII-1

STATION DELAY 30 SECONDS, FIRST TRAIN

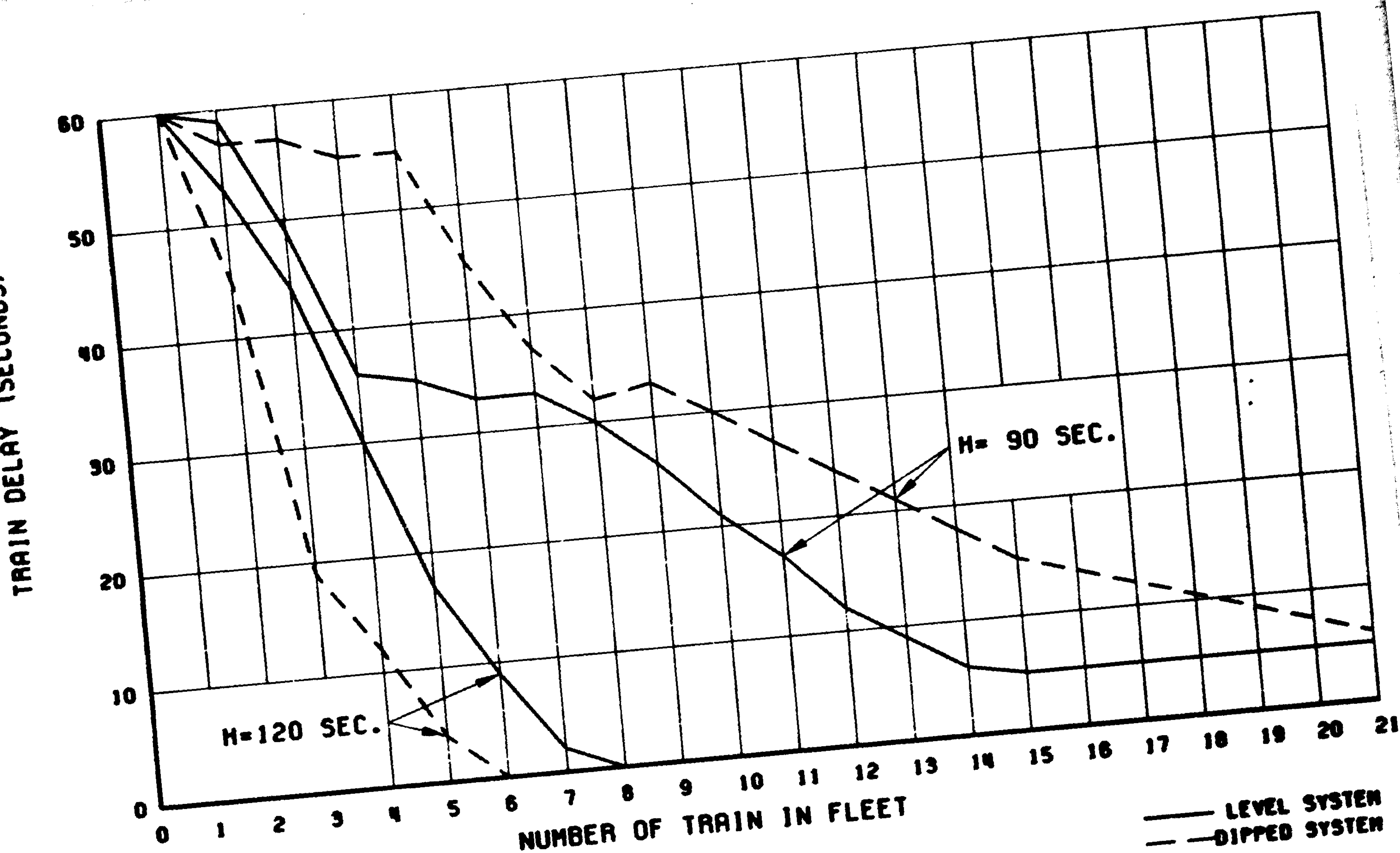


FIGURE NUMBER VII-2

STATION DELAY 60 SECONDS, FIRST ONE TRAIN

back as the second station on the level system. One dipped train was delayed approaching the second station.

Note, that for the most part, even where dipped system trains have greater delays, their overall run time is lower. Delays on the dipped system must exceed those of the level system by one minute or more in order for the run time advantage to be lost.

Station Delays - Major

Figure VII-3 presents the delays to trains at the end of the line as a result of 180-second station delays. The delays are significant at 180-second headways, and even larger at the shorter headways. At 90-second headways, the twenty-first train in both the dip and level systems is delayed. In the dipped system case, the delay would probably not dissipate before the peak period was over.

An estimate of the number of trains affected by a delay may be gained by dividing the delay by the slack headway. When scheduled headways are 90 seconds, the slack headways of the dipped and level systems are 3 and 9 seconds, respectively. Thus, about 60 dipped or about 20 level trains would dissipate this delay. Note that slope of the delay curve in Figure VII-3 equals the slack headway from train eight on. At larger operating headways the percentage difference in slack between the dipped and level systems is smaller so the performance is more equal.

Figure VII-4 presents delay statistics for the level system at both the middle of the line (eighth station) and the end of the line. In each case, the point is downstream of the location where the 180-second station delay occurred (i.e., the fourth station). In this case the results for the dipped and level systems were similar. Only the level system results are presented. As the figure shows, the delays to trains grow as they proceed on their way. This is so for two reasons, one of which reflects on the scope of this project.

In the absence of central control system, there is no slack within the run of a single train. Scheduled dwells at inline stations are not padded, and they are not reduced when a train arrives late. Neither are scheduled run times inflated to permit a train to catch up to its schedule. Thus, once a delay is incurred, it is carried along. Secondly, as the train delay is carried downstream, it continues to delay upstream trains. Although no slack is built into the schedule of a single train, slack exists between trains. This is the reason that delays to successive trains are generally reduced by approximately the value of the slack.

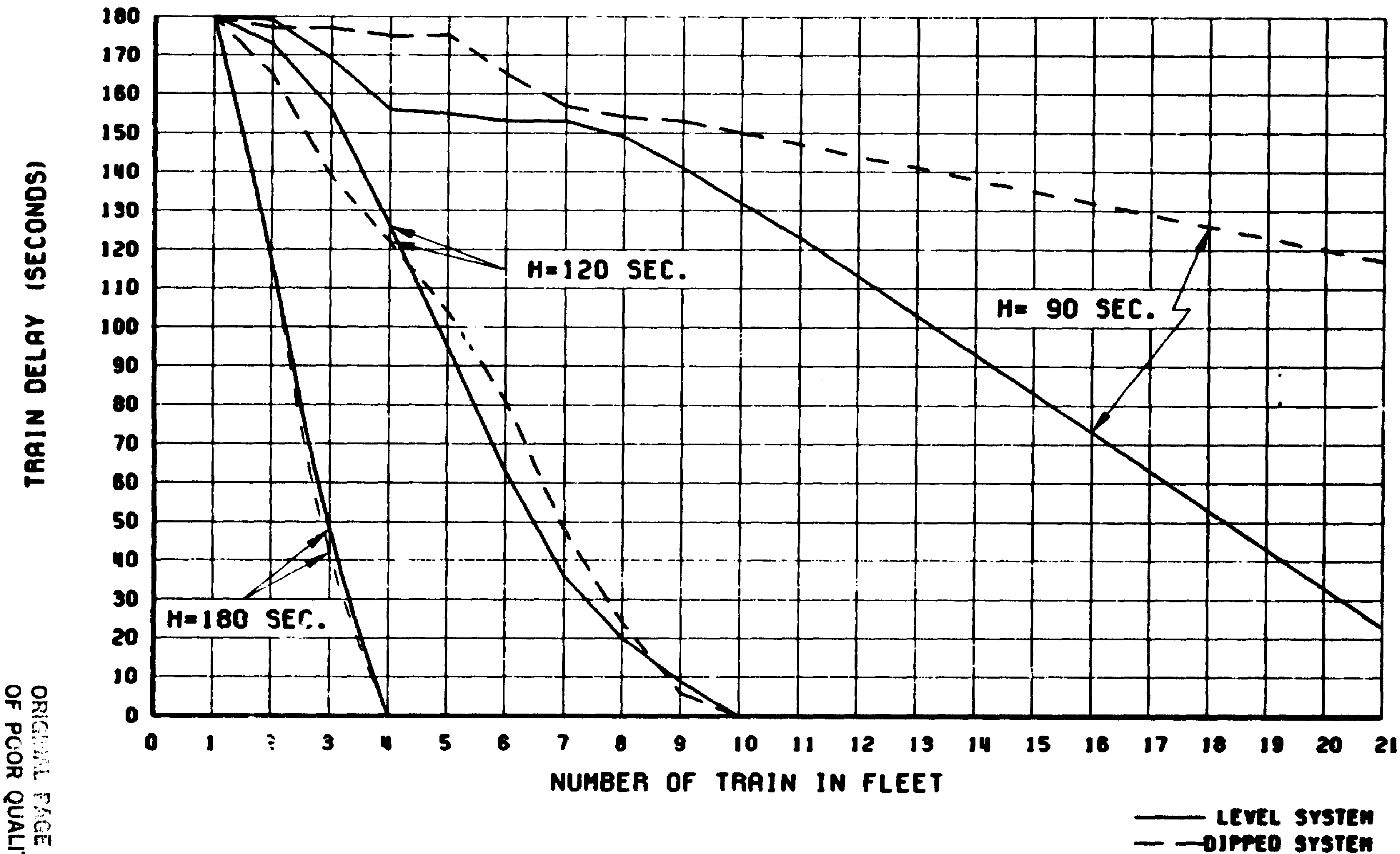


FIGURE NUMBER VII-3

STATION DELAY 180 SECONDS, FIRST TRAIN

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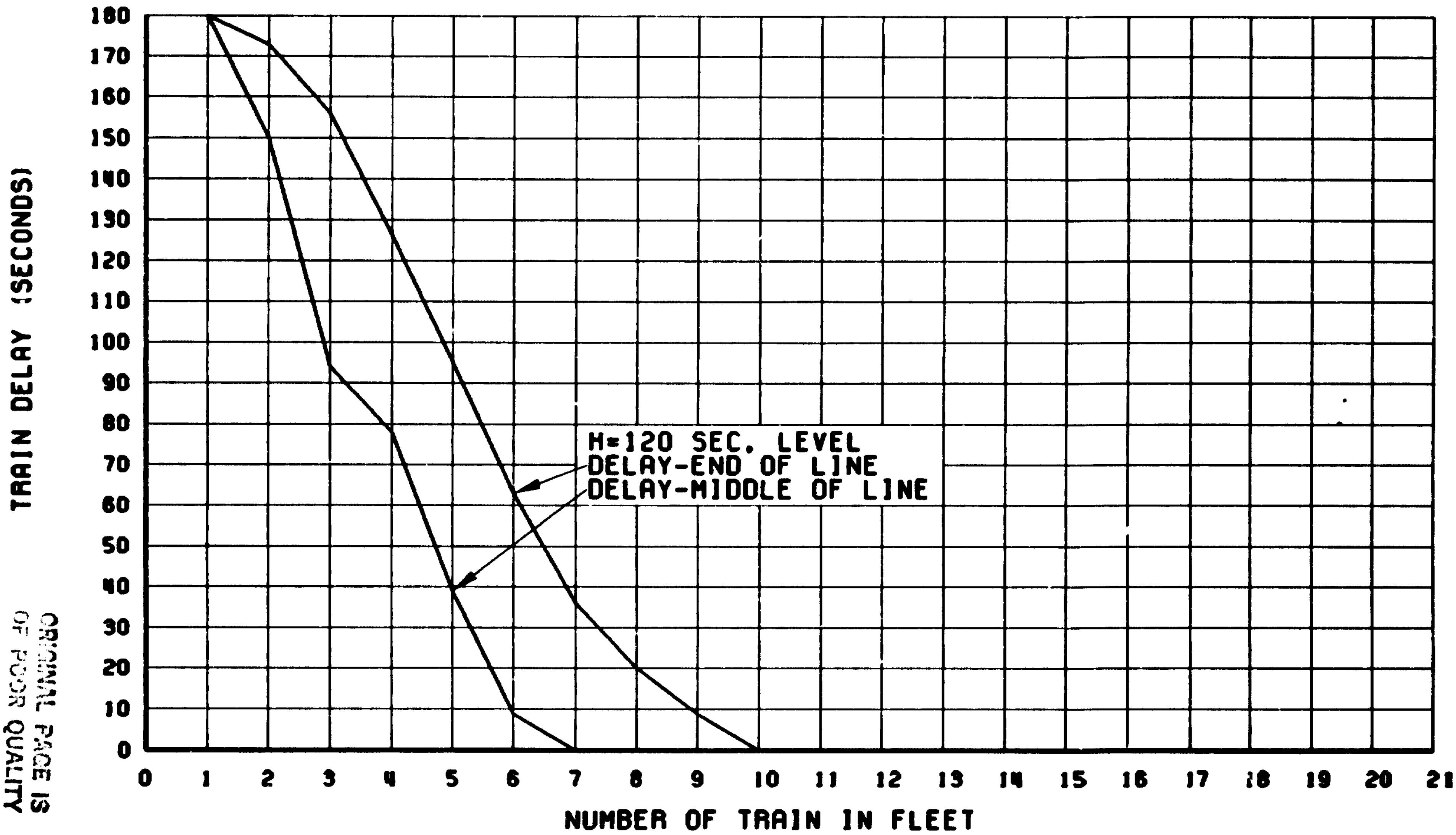

FIGURE NUMBER VII-4

STATION DELAY 180 SECONDS, FIRST TRAIN

GROWTH OF DELAY WITH DISTANCE FROM SOURCE

Figure VII-5 presents the results of the six-minute station delay for headways of 180 and 120 seconds. As expected, the delays are substantial and seriously impact operations. At 90 second headways, the failure was not materially attenuated in either system. All trains are delayed by nearly six minutes.

In the case of the 180-second station delay, upstream trains are delayed arriving at the second station although no trains are put in late. The 360-second failure does, however, back up to the terminal. Obviously, in the case of the major station delays, a dispatcher or central controller is needed. This is especially so in the dipped system where it is necessary to avoid trains being delayed or held on the grades.

Half Acceleration - Three Stations

As a class, acceleration failures cause smaller delays on the dipped system than on the level system because motive power is only a portion of total power in the dipped system. This acceleration failure, for example, causes a 34-second delay on the level system, but only a 26-second delay on the dipped system.

Unlike the station delay failures, this is a lingering failure. All trains in the fleet experience the same loss of propulsion. The loss of propulsion increases the time required for trains to clear away from the station. This in turn raises the minimum headway achievable.

At two- and three-minute headways, no trains are delayed beyond the delay caused by the acceleration failure. All level system trains are delayed 34 seconds, dipped system trains 26 seconds. At 90-second headways, the level system has enough slack. However, the dipped system does not. As a result the slack headway becomes negative and delays build upon the dipped system.

The second dipped train receives an extra delay of one second, the sixth is delayed ten seconds, the eleventh is delayed 44 seconds. Clearly, in the event of a power failure, a dispatcher must increase the scheduled headways of the dipped system above a threshold value. Every system has such a threshold value, which can be determined through simulation.

Half Acceleration - Systemwide

The systemwide acceleration failure is similar in nature to the failure of one substation, affecting three station pairs. However, in this case, acceleration is reduced for the entire line. Run time for all trains on the dipped system increases by 145 seconds. Run time for all trains on the level system is

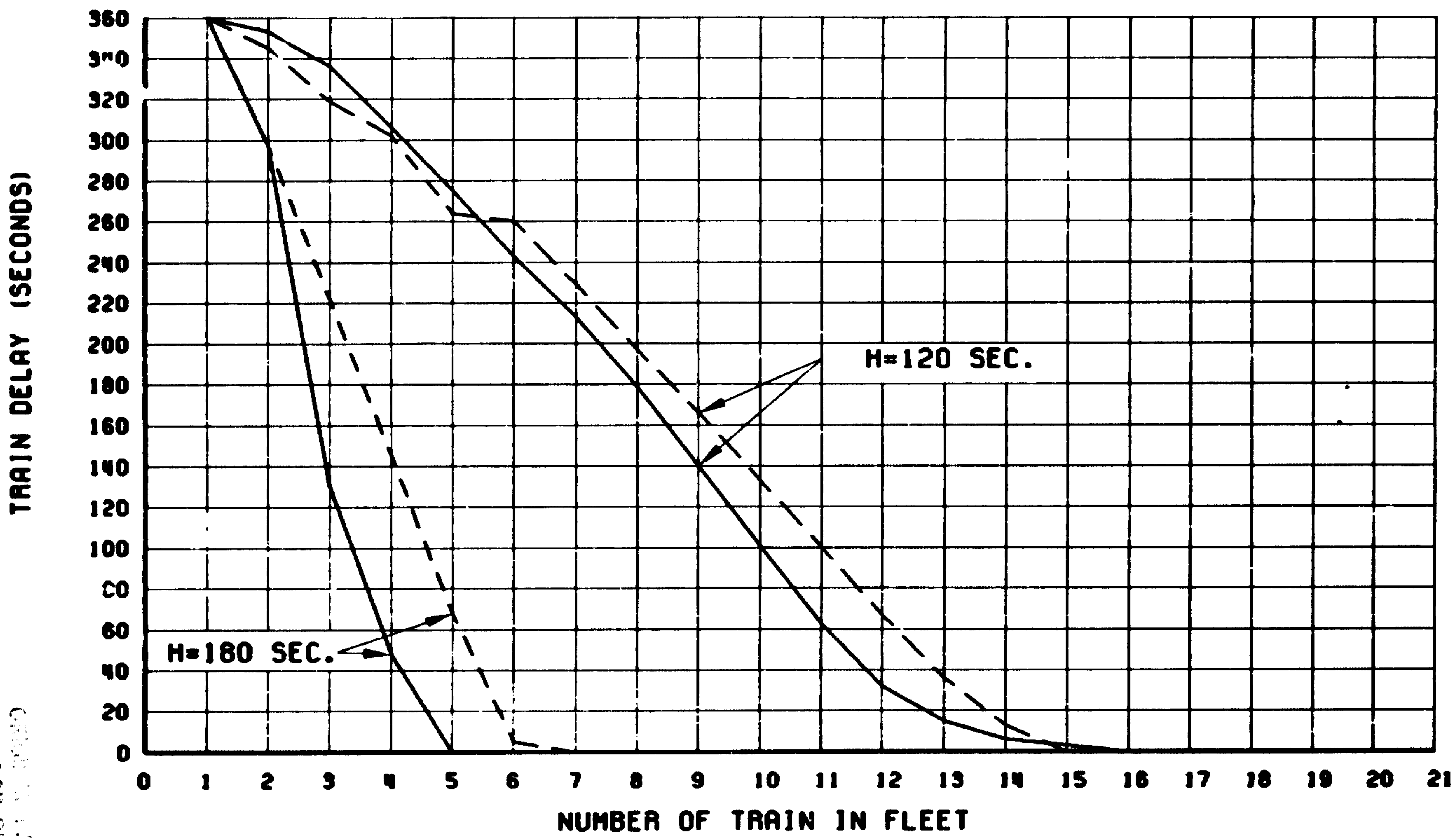

FIGURE NUMBER VII-5

STATION DELAY 360 SECONDS, FIRST TRAIN

increased by 203 seconds. The increases may be broken down by interstation distance:

Interstation Distance	Run Time Increase Per Station	
	Dipped System	Level System
2600 feet (4 stations)	7 seconds	8 seconds
5200 feet (6 stations)	9 seconds	13 seconds
7800 feet (2 stations)	12 seconds	18 seconds
13000 feet (3 stations)	13 seconds	19 seconds

The run time increase for the 13,000-foot stations is the maximum that would occur because trains reach the 75-mph speed limit, even at half acceleration. The increase is greater for stations spaced more widely apart because more acceleration occurs.

The results of this simulation are similar to the failure of one substation. The lingering acceleration failure reduces system capacity. However, none of the 7800-foot or 13000-foot stations were affected by the previous failure. Since the systemwide failure causes the greatest run time increases at the longest interstation distances, the impact on capacity is also greatest there.

Although the system has sufficient slack to avoid additional delays at 180- and 120-second headways, neither system can operate at 90-second headways. The dipped system handles headways of 105 seconds and the level system handles 93-second headways. Thus, when trains are dispatched at 90-second headways, delays build up. This occurs more rapidly for the dipped system because the slack headway is more negative than that of the level system. Should such a failure occur in either system, the dispatcher would have to adjust the schedule.

75% Acceleration - One Train

This failure increases the run time of the failed train by 50 seconds on the dipped system (from 27 minutes, 41 seconds to 28 minutes, 31 seconds) and by 69 seconds on the level system (from 28 minutes, 42 seconds to 29 minutes, 51 seconds). Unlike the station delays which occur to one train, at one location, this failure builds up as the train moves along.

Figure VII-6 presents the results of this experiment. No delays occur at 180-second headways. Several aspects of the figure are noteworthy, even curious. The delays at 90-second headways on the level system seem to be lower than at 120-second headways. At two-minute headways the delays on the dipped system are smaller and less extensive than on the level system, while at

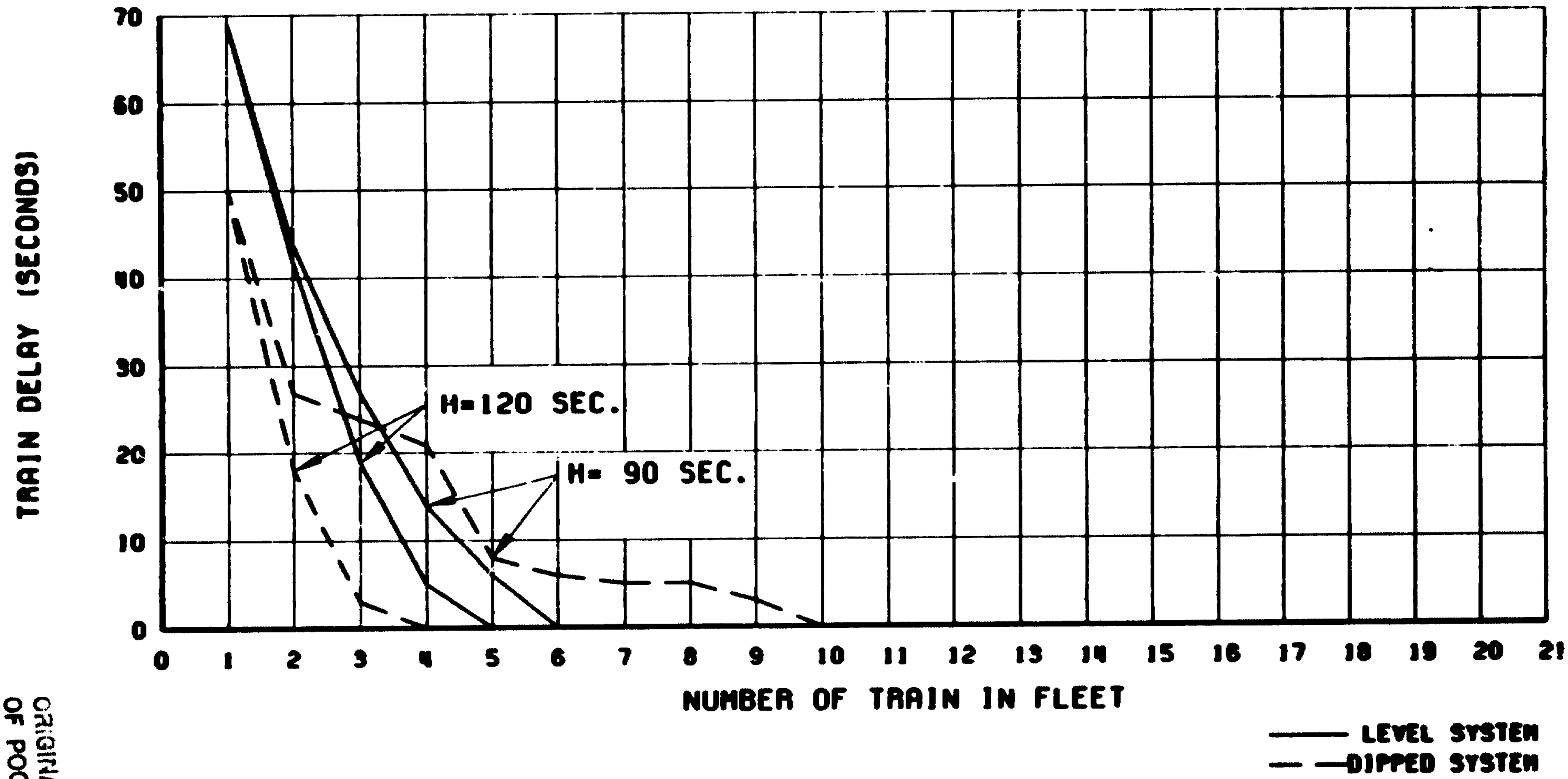

FIGURE NUMBER VII-6

75% ACCELERATION - FIRST TRAIN

90-second headways, the ninth dipped train is delayed but the fifth level train has no delay.

The explanation for the delays on the level system being greater at 120-second headways than at 90-second headways lies in the definition of delay. Delay is measured by comparing the run times of corresponding trains with and without the failure. The run times of trains without the failure are presented above in Table VI-2. Note that at 120-second headways, run time increases by only three seconds from the first to the last train in the fleet. However, at 90-second headways, the second train is delayed 28 seconds and the third train 51 seconds. The maximum delay of 64 seconds is quickly achieved. This delay is nearly the same as that caused by the acceleration failure. Thus, the incremental delay caused by the failure rapidly dissipates.

The delays on the level system are more extensive at 120-second headways because the size of the initial delay is 19 seconds greater than on the dipped system. At 90-second headways, the larger slack headway of the level system is the reason the delay is attenuated sooner, even though the delay to the second train is larger.

Top Speed Limit - One Station

The top speed limit is imposed between the first and second stations. The 20-mph limit adds 60 seconds of run time to the dipped system and 64 seconds to the level system trains. The 30-mph limit increases run times on the dipped system by 31 seconds and by 32 seconds on the level system.

The 30-mph limit does not create any additional delays beyond the half minute directly resulting from the failure for either the dipped or level system.

Scheduled headways of 180 or 120 seconds can be operated with the 20 mph speed limit for either the dipped or level system. In such cases, no additional delay results beyond the one-minute failure. Thus, the run times for dipped and level system trains are 60 and 64 seconds more than the corresponding times in Table VI-2.

The 20-mph limit is, however, too low a speed to permit operation at 90-second headways. The minimum headway the dipped system permits is 107 seconds. such delays result on the level system that the minimum headway is 133 seconds. In this case the level system is oversaturated. The dispatcher should obviously adjust the schedule to two-minute headways.

REFERENCES

Jet Propulsion Laboratory, "Alternative Concepts for Underground Rapid Transit Systems," TR No. DOT-TST-77-31,I Pasadena, California, 1977.

Weiss, D.M. and D.R. Fialkoff, "Analytical Approach to Railway Signal Block Design," ASCE Transportation Engineering Journal, February 1974.

APPENDIX

a. Car Characteristics

The following the car characteristics and train resistance formulas are used in the study.

1. Weight = 36 tons/car + 6 tons passengers/car
   Length = 75 feet/car
   axles = 4/car

2. Tractive effort (TE) curve per car (four cars/train, all motorized). Linear interpolation is used between speeds.

Speed (mph)	0	30	34	39	44	50
TE (lbs)	12400	12400	11500	9850	8750	6400

Speed (mph)	55	60	65	70	75
TE (lbs)	5000	4100	3300	2800	2350

3. Nominal braking rate (BR) curve. Linear interpolation is used between speeds.

Speed (mph)	0	50	75
BR (mphps)	2.2	2.2	1.65

4. Train resistance equations. The Davis resistance formula is used. The formula and its parameters are:

$$(AW + nB)N + (CWN)V + (D+E(N-1))XV^2$$

A = 1.3 , journal friction factor, lbs/ton
B = 29.0 , journal friction factor, lbs/axle
C = 0.045 , flange friction factor, lbs/ton/mph
D = 0.0024 , lead car wind resistance factor, $lbs/(ft\text{-}mph)^2$
E = 0.00034, trailing cars wind resistance factor, $lbs/(ft\text{-}mph)^2$

W = weight/car = 36 tons
n = axles/car = 4
N = cars/train = 4
X = cross sectional area = 90 sq. ft.
V = car speed (mph) = variable

b. Signal Block Modules

Two modular signal block designs were developed for this study, one for the level and one for the dipped guideway.

The modules contain the blocks and signal logic for the four interstation distances. The following tabulations contain: block length (feet), signal logic code, grade and a station presence indication for each module. The list of all signal logic codes is given in the next section.

Level Guideway

Interstation Distance	Block Length (feet)	Signal Logic Code	Average Grade (%)	Station
5200'	300	400		X
	650	420		
	650	420		
	1650	421		
	850	422		
	575	401		
	525	401		
	300	400		X
2600'	300	400		X
	650	410		
	650	411		
	475	411		
	525	411		
	300	400		X
7800'	300	400		X
	650	430		
	650	430		
	1950	431		
	2300	432		
	850	433		
	575	401		
	525	401		
	300	400		X
13000'	300	400		X
	650	440		
	650	441		
	2700	441		
	2900	441		
	2300	442		
	1500	443		
	900	444		
	575	401		
	525	401		
	300	400		X

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Dipped Guideway

Interstation Distance	Block Length (feet)	Signal Logic Code	Average Grade (%)	Station
5200'	300	1	0	X
	560	100	-2.8	
	740	101	-6.0	
	700	112	0	
	2000	107	0	
	500	106	+6.0	
	400	9	+3.43	
	300	1	0	X
2600'	300	2	0	X
	870	20	-2.41	
	630	21	0	
	800	22	2.63	
	40	1	0	X
	260	2	0	X
7800'	300	1	0	X
	560	200	-2.8	
	740	201	-6.0	
	700	202	0	
	3000	203	0	
	1200	7	0	
	600	6	+6.0	
	700	5	+3.43	
	300	1	0	X
13000'	300	1	0	X
	560	300	-2.8	
	740	301	-6.0	
	700	302	0	
	3000	302	0	
	2900	302	0	
	2300	303	0	
	1200	7	0	
	600	6	+6.0	
	700	5	+3.43	
	300	1	0	X

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c. Safe Braking Distance Parameters

The signal block design process used Gibbs & Hill proprietary computer programs to calculate the safe braking distance (SBD) required to transmit each speed in each block.

The SBD is based on a 6.5-second reaction time and a set of braking rates which are derated 25 percent from the nominal. During the reaction time, a train is assumed to maintain its speed for 3 seconds, then accelerate at full power for 2 seconds, then maintain this speed for 1 second. At the end of the reaction time, brakes are assumed fully applied as follows:

Speed (mph)	0	50	75
Safety Braking Rate (mphps)	1.65	1.65	1.24

Linear interpolation is used between speeds.

d. Signal Logic Codes

The following is the portion of the TRANSPORT data base containing all signal logic codes. Each code contains a speed to be transmitted in a given block if the specified number of blocks ahead are clear. The various speeds in a code appear in descending order. If less than the minimum number of blocks ahead are clear, a 0-mph command is sent.

Example: Signal logic #1 is used in most station blocks on the dipped guideway. If 3 or more blocks ahead are clear, a 40 mph command is sent to the train in the station block. If two blocks are clear, a 22 mph command is sent. If less than 2 are clear, a 0 mph command is sent.

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Signal Logic Code	Clear Blocks Ahead	Speed (mph)	Clear Blocks Ahead	Speed (mph)	Clear Blocks Ahead	Speed (mph)
1	3	40	2	22		
2	2	40	1	22		
5	5	60	4	45	2	28
6	6	75	3	50	1	28
7	6	75	2	50		
9	5	60	3	45	2	28
20	5	60	3	50		
21	6	60	4	50	3	40
22	6	60	4	45	3	28
100	4	75	3	55		
101	3	75	2	55		
102	5	75	2	55		
106	6	60	3	40	2	28
107	7	75	4	55	2	40
112	3	75	1	55		
200	6	75	3	55		
201	3	75	2	55		
202	2	75	1	55		
203	4	75	2	55		
300	3	75				
301	2	75				
302	2	75	1	55		
303	4	75	2	55		
400	2	40	1	22		
401	5	60	3	40	2	28
402	5	75	3	55	1	28
410	4	55	3	40		
411	4	55	3	40	2	28
420	4	75	2	55		
421	6	75	3	55		
422	7	75	4	55	2	35
430	3	75	2	55		
431	3	75	1	55		
432	6	75	3	55		
433	7	75	4	55	2	35
440	3	75	2	55		
441	2	75	1	55		
442	4	75	2	55		
443	6	75	3	55		
444	6	75	4	55	2	35